URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Tunable Frequency Selective Surface Design Using Automated Random Optimization

Farzad Mir[1+], Lida Kouhalvandi[2+*], and Ladislau Matekovits[3+◇#]
[+]Department of Electronics and Telecommunications, Politecnico di Torino, Turin, Italy
[*]Department of Electronics and Communication Engineering, Istanbul Technical University, Istanbul, Turkey
[◇]Department of Measurements and Optical Electronics, Politehnica University Timisoara, Romania
[#]National Research Council of Italy, 10129 Turin, Italy
farzad.mir@studenti.polito.it [1], kouhalvandi@itu.edu.tr [2], ladislau.matekovits@polito.it [3]

Abstract

We present an automated approach to design a high performance, tunable frequency selective surface (FSS). The main goal of this study is to provide the *simultaneous* optimization of the FSS structure in two states of the 4 incorporated varactors, aiming to get an acceptable polarization filtering and polarization control. Generally, microwave designs are dealing with a large amount of data and they depend on the engineer's experiences. In order to get rid of this dependency and providing a ready-to-fabricate layout, we propose an optimization-oriented method based on the random optimization (RO). The RO method is applied in an automated environment where HFSS and Matlab are collaborating together forming a co-simulation platform where the design parameters are optimized up to achieve suitable output performances.

1 Introduction and motivation

Frequency selective surfaces (FSSs) are usually made of an identical geometrical entity, called unit-cell; illuminated by an incident field, they act as filters, polarization converters, or exhibit other interesting features. FSSs can be widely used in various applications such as a cover for satellites, radomes, microwave stoves, etc.

The *passive* configurations have been widely used in the past, but recently *tunable* versions have received a more considerable attention [1] due to the possibility of real-time control of the transmission/reflection of the incident electromagnetic wave. Such feature can be efficiently exploited in many applications, from security to sensing, etc. The *dynamic*, tunable, counterpart incorporates active devices, that requires biasing for their tunability. The presence of the active elements inserts losses, while the existence of the biasing network makes the structure more complex with respect to the simple construction of the passive arrangement. The increased complexity that represents additional degrees of freedom has a controversial double effect on the design: on one hand it allows control of the structure's response, while on the other hand it makes the design more complex. Due to the complexity of the microwave designs, optimization techniques can be employed to reduce it [2, 3, 4, 5, 6]. Recently, for designing FSSs, various optimization methods have been considered. Particle swarm optimization, distribution algorithm, gradient optimization algorithm, and ant colony optimization technique [7, 8, 9, 10, 11, 12] are just few of them. These methods are successful algorithms in designs circuits but the outcome also depends on the designer's experience since the optimization process is under their control and supervision. To avoid the subjectivity arisen due to this aspect, we see the need of providing a study where optimization is employed in an automated environment with a combination of numerical analyzer and electronic design automation (EDA) tools. The EDA tools such as HFSS, ADS, AWR, etc. are some of the commercially available tools in the design in the microwave field. However, when a huge amount of data is to be considered for optimization, the use of external codes can be considered, since they allow a more direct access to the data. Among the possible platforms that can be used to implement independent optimizer one is Matlab.

In this work, we present the design and implementation of an FSS with the Random Optimization (RO) where the dimensions of the geometry of the FSS are achieved automatically. Importantly, as all the process is performing automatically, there is no human interruption in the optimization of the shape of the FSS. The automated environment is created using two commercial software, namely HFSS and Matlab. The result is the high performance FSS design with acceptable and suitable properties. Hence, without any dependency to any designer's experience, the ready-to-fabricate layout can be generated.

The initial design of FSS is created by providing two circular ring resonators with different radius dimensions. Two orthogonal microstrip lines parallel to the edges of the unit cell are then added to the structure and connect the two rings and intersect in the center. In order to tune the designed FSS, three via-holes are considered which are connected to the biasing lines that are located below the main structure described above. The biasing network consists of

other two microstrip lines embedded in the dielectric supporting the main structure. They are parallel to the two microstrip lines of the main structure and are located at different levels (at a distance of 0.8 mm and symmetrically with respect to the middle of the dielectric layer) to avoid short circuit between them. Their role is to bias some diodes located within the main structure. The redundancy of the via-holes aims to avoid symmetry-breaking of the structure. A CAD model of the structure is reported in Fig. 1.

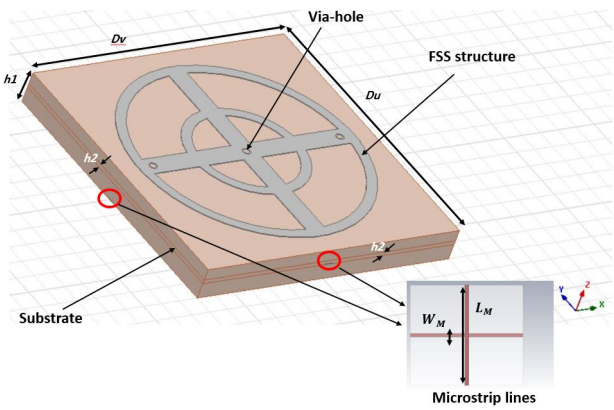

Figure 1. Geometry of the initial unit cell with the leading dimensions

In this paper, tunability is implemented by incorporating diodes in the main structure. To do so, the structure has to be modified in such a way to incorporate these lumped elements. In particular, we considered 4 slots in the main structure that will accommodate as many varactors to be identically biased. These slots are located along the radially running microstrip lines and in between the two ring resonators.

Using diodes in the slots will provide them with two main conditions: (*i*) open circuit and (*ii*) short circuit, respectively. The open circuit condition corresponds to low voltage, and is equivalent to a capacitor. Contrarily, the short-circuit configuration is the model for small values of resistor at high biasing voltage. Using an appropriate model for the diodes, it has been recently demonstrated [13] that the presence of the diodes in the two working conditions mentioned above gives similar response as for the non-loaded main structure and for the non-loaded structure with cuts.

The geometrical variation, i.e., insertion of the slots, will give rise to a second geometry, that has to be optimized at the same time with the main one. The *simultaneous* optimization of the two structures in Fig. 2, namely the main (initial) one and the second one with cuts represents the main novelty of the present work.

This work is organized as follows: Section II presents the proposed optimization method where HFSS with Matlab are working together. The validation of the method is proved by designing and optimizing the FSS that is described in Sec.III. The conclusions of this work are provided in Sec. IV.

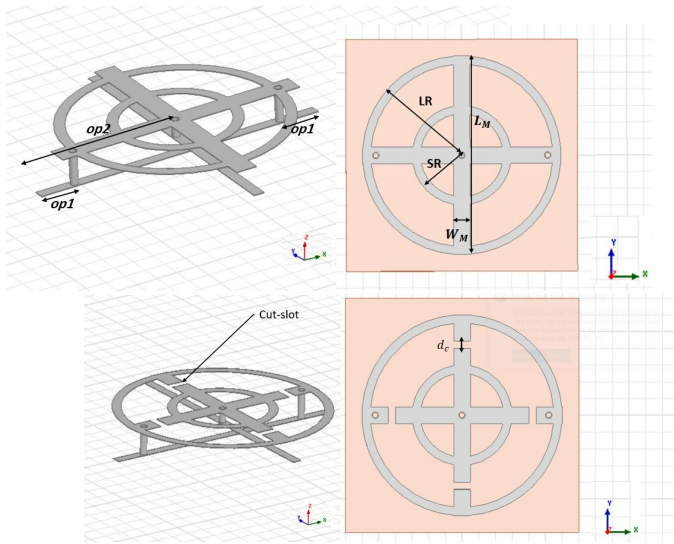

Figure 2. Initial geometry (top), geometry with the cuts (bottom)

2 Automated Random Optimization method for the FSS design

The RO, as its name suggests, is the process of randomly iterating the design parameters up to achieving suitable values of them [14]. In this method, the design parameters are iterated, i.e., increased or decreased, randomly up to achieving desired output performance. Fabrication constrains, i.e. minimum distance between microstrip lines, or their minimum width, are also employed in the optimization process and passed to the electromagnetic (EM) simulations in the EDA tools.

For our problem consisting of the design of a tunable FSS, we employ random optimization (RO) method for simultaneously optimize the two configurations considering their constitutive design parameters aiming to achieve the suitable output performances for both of them. The applied method is performed in an automated environment where HFSS with Matlab are co-operating together [15] for optimizing the FSS without any human interruption. As described in [16], providing an automated environment can pave the way of researchers to get rid of any designer's experience and to easily deal with the challenging design problems. The algorithm in Fig. 3 presents the proposed optimization method for design the high performance FSS.

Once the initial geometry has been set, the automated environment is created where HFSS is working in the background and Matlab is handling and elaborating all the simulation results. Hence, the effort for preparing the data for optimizing the circuit is substantially reduced. Then the RO algorithm is applied where the design parameters are randomly iterated and the parameters are either increasing or decreasing automatically. This iteration loop is continued up to attaining the suitable output performances.

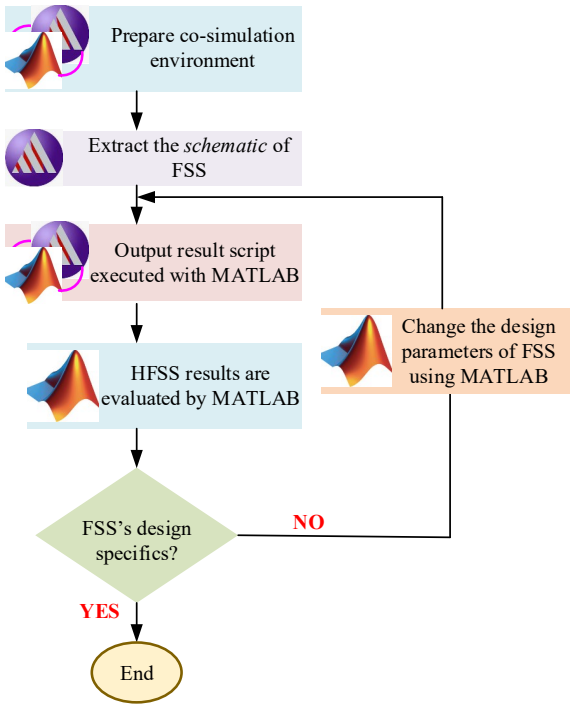

Figure 3. Proposed automated RO algorithm for optimizing FSS.

3 Practical FSS Design and Optimizations

This section presents the structure of designed FSS. Figure 1 illustrates the main structure of $D_u \times D_v = 14 \times 14$ mm built on FR-4 substrate ($\varepsilon_r = 4.3$ and $\tan\delta = 0.025$) with thickness of $h1 = 1.58$ mm. Our proposed structure described in the previous section and shown in Fig. 2 (top) is characterized by the following *initial* dimensions: external radius of the large circle is LR= 6 mm, external radius of the small circle SR= 3 mm, width of the two rings $w = 0.5$ mm. Each of the two bias microstrip lines have the same width ($W_M = 1$ mm) and length ($L_M = 12$ mm).

The three via-holes serves connecting the main structure to the biasing lines. These later are reported in the inset of the Fig. 1. First via-hole is located on the left side of the structure $op1 = 1.8$ mm (this distance is measured from the edge of the FSS), and the second one is placed in the center of the FSS $op2 = 7$ mm. The third one has the same behavior as the first one but in order to keep the symmetric structure it is created on the right of the structure with the same distance of $op1$. Use of this redundancy aims to reduce symmetry breaking, hence asymmetric answer of the circuit. Figure 2 illustrates the connection of via-holes to the biasing microstrip lines present for both the main and cut-slot structures. The reported values for the parameters refer to the initial design before applying the optimization process.

Figure 4 shows the results in terms of transmission coefficient (TC) for initial main structure for both TE (denoting E field parallel to x axis) and TM incidences (E field parallel to x axis); results for both the initial and optimized configurations are proposed. The initial structure for the main design has two frequency bands of interest (-10 dB): the first one is from 6.7 GHz to 9.5 GHz (2.8 GHz) and the second one covers 800 MHz (11.7 GHz - 12.5 GHz). After applying the optimization, the first band does not noticeably change but there is an increase of the second bandwidth up to 2.2 GHz, and an up shift of its central frequency. For TM incidence, the bandwidth of initial design and optimized one is almost constant but a shift in frequency happens from 11.2 GHz to 12.9 GHz for initial and optimized structure, respectively.

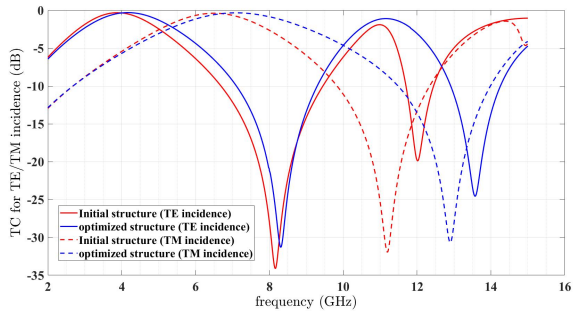

Figure 4. Transmission coefficient (TC) for initial and optimized main structure.

Figure 2 (bottom) reports the structure with the cut-slots. The result for this configuration for both initial and optimized designs are shown in Fig. 5 for TE and TM incidences. Following the optimization, for TE incidence, first frequency band notch shifts from 5 GHz to 5.8 GHz but maintaining almost the same bandwidth. Also, the second frequency band exhibits a frequency shift toward higher values. For the TM case similar behaviour can be noticed.

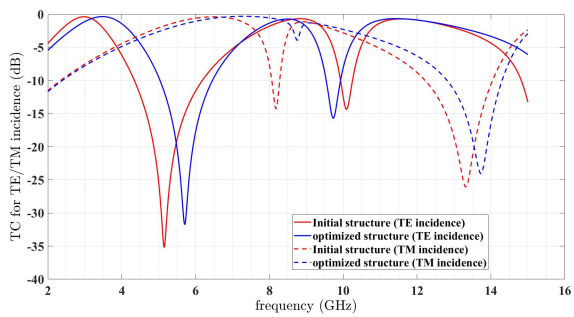

Figure 5. Transmission coefficient (TC) for initial and optimized cut-slot structure.

From the plots above it results that there are frequency bands where the FSS acts as polarization filter (only one polarisation is transmitted). Moreover, analysing the phase of the transmitted fields (not reported) for the different cases allows identifying frequency bands where the structures can be use as polarizer transformer from linear to circular. Different working regimes have been identified.

4 Conclusion

In this work, we study the implementation of the RO method in an automated environment where HFSS and Matlab are collaborating together. The presented method is used in designing and optimizing a tunable FSS, based on two equivalent states of the involved diodes, which paves the way of designers for not challenging with huge amount of data. The FSS design is provided in HFSS and Matlab handles the optimization in order to find the suitable dimensions of the FSS geometry.

References

[1] S. Ghosh and K. V. Srivastava, "A dual-band tunable frequency selective surface with independent wideband tuning," *IEEE Antennas and Wireless Propagation Letters*, vol. 19, no. 10, pp. 1808–1812, 2020.

[2] T. Gombor and J. Pávó, "Numerically efficient modeling of frequency selective surfaces in broad frequency range," *IEEE Transactions on Magnetics*, vol. 51, no. 3, pp. 1–4, 2015.

[3] A. O. Boryssenko, S. M. Gillette, and M. Y. Koledintseva, "Nonlinear loss model in absorptive-type ferrite frequency-selective limiters," *IEEE Transactions on Microwave Theory and Techniques*, vol. 67, no. 12, pp. 4871–4880, 2019.

[4] A. Ludvig-Osipov and B. L. G. Jonsson, "Evaluation of the electric polarizability for planar frequency-selective arrays," *IEEE Antennas and Wireless Propagation Letters*, vol. 17, no. 7, pp. 1158–1161, 2018.

[5] B. Döken and M. Kartal, "Easily optimizable dual-band frequency-selective surface design," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 2979–2982, 2017.

[6] M. S. M. Mollaei, "Narrowband configurable polarization rotator using frequency selective surface based on circular substrate-integrated waveguide cavity," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 1923–1926, 2017.

[7] M. A. Rodriguez Barrera and W. P. Carpes, "Bandwidth for the equivalent circuit model in square-loop frequency selective surfaces," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 11, pp. 5932–5939, 2017.

[8] S. Genovesi, R. Mittra, A. Monorchio, and G. Manara, "Particle swarm optimization for the design of frequency selective surfaces," *IEEE Antennas and Wireless Propagation Letters*, vol. 5, pp. 277–279, 2006.

[9] M. Zhao, X. Yu, Q. Wang, P. Kong, Y. He, L. Miao, and J. Jiang, "Novel absorber based on pixelated frequency selective surface using estimation of distribution algorithm," *IEEE Antennas and Wireless Propagation Letters*, vol. 14, pp. 1467–1470, 2015.

[10] R. Zhao, B. Gong, F. Xiao, C. He, and W. Zhu, "Circuit model analysis of switchable perfect absorption/reflection in an active frequency selective surface," *IEEE Access*, vol. 7, pp. 55 518–55 523, 2019.

[11] D. Z. Zhu, M. D. Gregory, P. L. Werner, and D. H. Werner, "Fabrication and characterization of multiband polarization independent 3-d-printed frequency selective structures with ultrawide fields of view," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 11, pp. 6096–6105, 2018.

[12] D. Z. Zhu, P. L. Werner, and D. H. Werner, "Design and optimization of 3-d frequency-selective surfaces based on a multiobjective lazy ant colony optimization algorithm," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12, pp. 7137–7149, 2017.

[13] M. Kiani, M. Tayarani, A. Momeni, H. Rajabalipanah, and A. Abdolali, "Self-biased tri-state power-multiplexed digital metasurface operating at microwave frequencies," *Opt. Express*, vol. 28, no. 4, pp. 5410–5422, Feb 2020. [Online]. Available: http://www.opticsexpress.org/abstract.cfm?URI=oe-28-4-5410

[14] G. Xu, S. V. Hum, and G. V. Eleftheriades, "A technique for designing multilayer multistopband frequency selective surfaces," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 2, pp. 780–789, 2018.

[15] C. Jarufe, R. Rodriguez, V. Tapia, P. Astudillo, D. Monasterio, R. Molina, F. P. Mena, N. Reyes, and L. Bronfman, "Optimized corrugated tapered slot antenna for mm-wave applications," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 3, pp. 1227–1235, 2018.

[16] L. Kouhalvandi, O. Ceylan, and H. B. Yagci, "Power amplifier design optimization with simultaneous cooperation of eda tool and numeric analyzer," in *2018 18th Mediterranean Microwave Symposium (MMS)*, 2018, pp. 202–205.